

# THE CONTRIBUTIONS OF INTERACTIVE BINARY STARS TO DOUBLE MAIN SEQUENCE TURN-OFFS AND DUAL RED CLUMP OF INTERMEDIATE-AGE STAR CLUSTERS

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## ABSTRACT

Double or extended main-sequence turn-offs (DMSTOs) and dual red clump (RC) were observed in intermediate-age clusters, such as in NGC 1846 and 419. the DMSTOs are interpreted as that the cluster has two distinct stellar populations with differences in age of about 200-300 Myr but with the same metallicity. The dual RC is interpreted as a result of a prolonged star formation. Using a stellar population-synthesis method, we calculated the evolutions of binary-star stellar population (BSP). We found that binary interactions and merging can reproduce the dual RC in the color-magnitude diagrams of an intermediate-age cluster, whereas in actuality only a single population exists. Moreover, the binary interactions can lead to an extended MSTO rather than DMSTOs. However, the rest of main sequence, subgiant branch and first giant branch are hardly spread by the binary interactions. Part of the observed dual RC and extended MSTO may be the results of binary interactions and merger.

*Subject headings:* galaxies: star clusters: general — globular clusters: general — binaries: general

## 1. Introduction

It has always been accepted that a star cluster (SC) is composed of stars belonging to a single, simple stellar population with a uniform age and chemical composition. In recent years, however, due to the increase in spatial resolution and photometric accuracy, it has been discovered that some SCs have unusual structures in their observed color-magnitude diagrams (CMDs). For example, NGC 2173 in the Large Magellanic Cloud (LMC) has

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an unusually large spread in color about its main-sequence turn-off (MSTO) (Bertelli et al. 2003); Omega Centauri exhibits a main sequence (MS) bifurcation (Piotto et al. 2005); NGC 2808 possesses a triple MS split (Piotto et al. 2007); and other clusters also contain multiple stellar populations (Milone et al. 2009, 2010). More interesting discoveries are that the intermediate-age massive clusters in the LMC, such as NGC 1846, 1806, and 1783, possess double main-sequence turn-offs (DMSTOs) on their CMDs (Mackey & Broby Nielsen 2007; Mackey et al. 2008; Milone et al. 2009). Moreover, Goudfrooij et al. (2009) found that the spread of the MSTO is fairly continuous rather than strongly bimodal. Mackey et al. (2008) and Goudfrooij et al. (2009) argued that these clusters do not possess a significant line-of-sight depth or internal dispersion in  $[\text{Fe}/\text{H}]$ , or suffer from significant differential extinction. Mucciarelli et al. (2008) showed that spreads in  $[\text{Fe}/\text{H}]$  in SCs like NGC 1783 are very small. The apparent homogeneity in  $[\text{Fe}/\text{H}]$  of all stars in NGC 1846 indicates that capture of pre-existing field stars during cluster formation seems to hard to explain the DMSTOs (Mackey et al. 2008; Goudfrooij et al. 2009). The DMSTOs are interpreted as that the clusters have two distinct stellar populations with differences in age of  $\sim 200\text{-}300$  Myr but with similar metal abundance (Mackey & Broby Nielsen 2007; Mackey et al. 2008). Moreover, Glatt et al. (2008) found multiple MSTOs (MMSTOs) in NGC 419 in the Small Magellanic Cloud, and Girardi et al. (2009) found two distinct red clumps (RC) in this cluster. These observational results are challenging the traditional picture.

In order to understand how a cluster can contain multiple populations with different ages, many scenarios were proposed. Mackey & Broby Nielsen (2007) put forward the scenario of merger of two (or more) SCs. However, Goudfrooij et al. (2009) pointed out that this scenario seems unlikely. Bekki & Mackey (2009) simulated the merger of a SC with a giant molecular cloud (GMC). They found that this merger can produce a second-generation of stars that are required to explain the DMSTOs. However, in order to obtain the differences in age of  $\sim 200 - 300$  Myr, this scenario require rather strongly constrained ranges of GMC parameters such as their spatial distribution, mass function, and chemical composition (Goudfrooij et al. 2009; Bastian & de Mink 2009). D’Ercole et al. (2008) and Goudfrooij et al. (2009) put forward the scenario of formation of a second generation of stars from the ejecta of first generation asymptotic giant branch stars. In this scenario, the young second generation is usually less than the first one (Bastian & de Mink 2009), which is not consistent with observations (Milone et al. 2009). Recently, using two scaling relations to mimic the effects of rotation, Bastian & de Mink (2009) considered the effect of rotation on stellar evolutions. They found that stellar rotation in stars with masses between  $1.2$  and  $1.7 M_{\odot}$  can mimic the effect of a double population when rotation rates reach 20-50 per cent of the critical rotation, whereas in actuality only a single population exists. However, Rubele et al. (2010) and Girardi et al. (2011) argued that rotational effect could not explain

the presence of MMSTOs. They proposed a prolonged star formation (PSF) to explain the MMSTOs and the dual RC. In Rubele et al. (2010) models, in order to reproduce the dual RC of NGC 419, a PSF of about 700 Myr is required. The dual RC was also found in NGC 1751 (Rubele et al. 2011). In order to explain this dual RC, a PSF of about 460 Myr is required (Rubele et al. 2011). This age spread is twice longer than  $\sim 200$  Myr estimated by Milone et al. (2009) using the method of isochrone fitting. Furthermore, recently, Keller et al. (2011) argued that the isolation of extended MSTO clusters to intermediate ages could be the consequence of observational selection effects.

In addition, binary stars of LMC clusters are unresolved even with Hubble Space Telescope (Milone et al. 2009). The binary system should appear as a single point-source object. Thus the unresolved binary systems may have contributions to the spread of MSTO. However, several investigators (Mackey et al. 2008; Goudfrooij et al. 2009; Milone et al. 2009) had found that unresolved binaries cannot alone reproduce the peculiar MSTO structures. Nevertheless, after a star in a binary system accretes mass from its companion, it will become younger apparently. Hence, interactive binaries may have contributions to the spread of MSTO. Goudfrooij et al. (2009) found that the younger populations in clusters are more centrally concentrated than the older populations. Thus the interactive binaries may be important in interpreting the observed CMDs. In this paper, using the Hurley rapid single and binary evolution codes (Hurley et al. 2000, 2002) and a stellar population-synthesis method, we investigated the contributions of interactive binaries to the DMSTOs and dual RC.

The paper is organized as follow. We show our stellar population-synthesis method in section 2. We present the results in section 3 and discuss and summarize them in section 4.

## 2. Stellar population synthesis

To investigate DMSTOs and dual RC of SCs, we calculated a binary-star stellar population (BSP). Stellar samples are generated by Monte Carlo simulations. The basic assumptions for the simulations are as follows. (i) The lognormal initial mass function (IMF) of Chabrier (2001) is adopted. (ii) We generate the mass of the primary,  $M_1$ , according to the IMF. The ratio ( $q$ ) of the mass of the secondary to that of the primary is assumed to be a uniform distribution within 0-1 for simplicity. The mass of the secondary star is then determined by  $qM_1$ . (iii) We assume that all stars are members of binary systems and that the distribution of separations ( $a$ ) is constant in  $\log a$  for wide binaries and falls off smoothly

at close separation:

$$an(a) = \begin{cases} \alpha_{\text{sep}}(a/a_0)^m & a \leq a_0; \\ \alpha_{\text{sep}}, & a_0 < a < a_1, \end{cases} \quad (1)$$

where  $\alpha_{\text{sep}} \approx 0.070$ ,  $a_0 = 10R_{\odot}$ ,  $a_1 = 5.75 \times 10^6 R_{\odot} = 0.13\text{pc}$  and  $m \approx 1.2$ . This distribution implies that the numbers of wide binary system per logarithmic interval are equal, and that approximately 50% of the stellar systems are binary systems with orbital periods less than 100 yr (Han et al. 1995). **However, binaries account for typically ~30-40% of all stars in the clusters of LMC, such as in NGC 1818 and 1806 (Elson et al. 1998; Milone et al. 2009).** (iv) The eccentricity ( $e$ ) of each binary system is assumed to be a uniform distribution within 0-1. With these assumptions, we calculated the evolutions of  $5 \times 10^4$  binaries with  $M_1$  between 0.8 and 5.0  $M_{\odot}$ .

The metal abundance  $Z$  of evolutionary models was converted firstly into  $[\text{Fe}/\text{H}]$ . Then the theoretical properties ( $[\text{Fe}/\text{H}]$ ,  $T_{\text{eff}}$ ,  $\log g$ ,  $\log L$ ) have been transformed into colors and magnitudes using the color transformation tables of Lejeune et al. (1998). The binaries with  $a \leq 10^6 R_{\odot}$  were treated as unresolved ones, while others were treated as resolved ones when we computed their colors and magnitudes.

### 3. Calculation results

Figure 1 shows the CMDs of the simulated BSP with  $Z = 0.008$  and age = 1.8 Gyr. The interactive binaries are shown in red, while non-interactive binaries are shown in green. The population of the brighter MSTO (bMSTO) is mainly from the unresolved binaries with  $q > 0.7$  and no interactions. The isochrones of single-star stellar populations (SSP) with the same  $Z$  but different ages are overplotted on the CMD in the right panel of Fig. 1. The stars that experienced binary interactions clearly deviate from the isochrone of non-interactive binaries in the region around MSTO, which leads to a large spread in color. The interactive binaries clearly produce an extended MSTO rather than bimodal MSTO. For main sequence **binary** stars with  $m_V < 22.5$  mag, **about 10% of the binary stars lie between the 1.8 and 1.5 Gyr isochrones in our models, not including the binaries on the 1.8 Gyr isochrone.** However, interactive binaries hardly affect the rest of MS, subgiant branch and first giant branch (FGB). Moreover, interactive binaries result in the appearance of a secondary RC (SRC) at about 0.5 mag below the main RC. The SRC is slightly bluer than the ridgeline of FGB stars. The contribution of non-interactive binaries to the SRC is negligible. The right panel of Fig. 1 shows that the ridge of the SRC is almost coincident with the isochrone of RC stars of the SSP with age = 1.2 Gyr. About 12% of core-helium burning (CHeB) **binary** stars are located between the 1.8 and 1.5 Gyr isochrones. However,

about 30% of CHeB **binary** stars are located between the main RC and 1.2 Gyr isochrone, not including **the binary** stars on the main RC but including those on 1.2 Gyr isochrone. The mass of the SRC stars is mainly located between 1.85 and 2.1  $M_{\odot}$ , while that of the main RC stars is less than 1.7  $M_{\odot}$ .

The dual RC was discovered in NGC 752, 7789 and 419 (Girardi et al. 2000, 2009) and NGC 1751 (Rubele et al. 2011). Cluster NGC 419 has an age of about 1.35 Gyr (Girardi et al. 2009). We computed a cluster with age = 1.3 Gyr and  $Z = 0.004$ . Its CMDs are shown in Fig. 2. Just as above results, the interactive binaries lead to a large spread in color in the region around MSTO, but they do not reproduce DMSTOs. However, the interactive binaries lead to the presence of a distinct SRC. The ridge of the SRC is almost coincident with the isochrone of RC stars of the SSP with age = 1.1 Gyr. This implies that the SRC produced by binary interactions has an apparent age of about 1.1 Gyr in our models, whereas actually it has an age of 1.3 Gyr. **For this dual RC, about 15% of binary stars** are located between the 1.3 and 1.1 Gyr isochrones, including the **binaries** on the 1.1 Gyr isochrone but not including those on 1.3 Gyr isochrone. The magnitude extension between main RC and SRC is about 0.35 mag. The mass of the SRC stars is mainly located between 1.85 and 2.05  $M_{\odot}$ , while that of the main RC stars is mainly located between 1.78 and 1.81  $M_{\odot}$ . For  $Z = 0.004$ , in stars more massive than about 1.88  $M_{\odot}$  (this value is about 2.0  $M_{\odot}$  for  $Z = 0.02$ ), helium-burning temperatures are reached at the center before electrons become degenerate there. For these stars, when they are on zero-age horizontal branch (ZAHB), their magnitudes decrease with decreasing mass. However, for the stars with  $M < 1.88 M_{\odot}$ , electrons in the hydrogen-exhausted core are highly degenerate before helium ignition occurs. When they are on ZAHB, their magnitudes increase rapidly with decreasing mass except for stars with  $M < 1.5 M_{\odot}$ . The magnitudes of ZAHB stars with  $M < 1.5 M_{\odot}$  increase very slowly with decreasing mass. For  $Z = 0.004$ , the evolutionary tracks of RC stars with mass between about 1.85 and 2.0  $M_{\odot}$  are very near each other in CMDs. Thus the interactive binaries with mass between about 1.85 and 2.0  $M_{\odot}$  can gather to form a SRC. Our calculations show that the SRC caused by binary interactions appears mainly in clusters with  $1.2 \text{ Gyr} < \text{age} < 3.0 \text{ Gyr}$ .

#### 4. Discussion and Conclusions

Milone et al. (2009) showed that the fraction of younger (brighter) population is about 75% in the case of NGC 1846. In our models, the ‘younger’ population are mainly from the merged binary systems and interactive binaries with mass transfer. The merging and mass transfer in binary systems can be affected by the distributions of separation ( $a$ ), eccentricity

( $e$ ) and mass-ratio ( $q$ ) of systems. We computed the BSP by using the distributions  $n(\log a) = \text{constant}$  (Hurley et al. 2002),  $n(e) = 2e$  and  $n(q) = 2q$  and the IMF of Salpeter (1955). However, the fraction of the interactive binaries are not obviously enhanced. We also computed the BSP using the distribution  $n(\log a) = \text{constant}$  and Gaussian distributions for  $e$  and  $q$ . The mean value and standard deviation of the Gaussian distributions is 0.5 and 0.13 for  $e$ , 0.6 and 0.1 for  $q$ , respectively. The values of the standard deviation are chosen in order to make the values of  $e$  and  $q$  are located between 0 and 1. In this simulation, **about 20% of binary stars lie between the 1.8 and 1.5 Gyr isochrones for the cluster with  $Z = 0.008$  and age = 1.8 Gyr; while for the RC of the cluster with  $Z = 0.004$  and age = 1.3 Gyr, about 30% of binary stars lie between the 1.3 and 1.1 Gyr isochrones.**

The mass of turn-off stars is about  $1.46 M_{\odot}$  for the cluster with  $Z = 0.008$  and age = 1.8 Gyr in our models. The evolutions of a wide binary system without mass transfer are similar to those of single stars with the same mass. However, the evolution of stars whose mass increased via mass accretion or merging is always slower than that of single stars with the same mass. For example, a mass-accreted star with  $M = 1.55 M_{\odot}$ , which was reached by accretion, just arrives at around MSTO at the age of 1.8 Gyr. However, a single star with an initial mass of  $1.55 M_{\odot}$  has left the MSTO at the same age. Thus the mass-accreted stars clearly deviate from the ridge of the isochrone in the region around MSTO and have an apparent younger age. The more the accreted mass, the more the deviation. Thus the spread of MSTO of BSP is continuous rather than bimodal. However, for the mass-accreted stars with  $M < 1.25 M_{\odot}$ , an increase in mass leads to a shift of their position in CMDs almost along MS. Therefore, the most of MS are hardly spread by binary interactions.

The SRC is almost made of the mass-accreted or merged stars whose mass is slightly more massive than the critical mass that is just enough to avoid electron-degeneracy occurring in stellar H-exhausted cores in our models. The stars with the critical mass usually evolve into RC at the age of about 1.1-1.2 Gyr (For the stars with  $Z \geq 0.04$ , this age can increase to about 1.3 Gyr). Hence, the SRC caused by interactive binaries should have an apparent age of about 1.1-1.2 Gyr, whereas actually it has an age as old as that of main RC. The apparent age of about 1.1-1.2 Gyr is consistent with the estimates of Rubele et al. (2011, 2010) for NGC 1751 and 419. The main RC stars passed through electron degeneracy. The magnitude of these stars increases with decreasing mass. The older the age of clusters, the lower the mass of main RC stars. Thus, the magnitude extension between main RC and SRC increases with age until the mass of the main RC is less than about  $1.5 M_{\odot}$ . Because the magnitude of ZAHB stars with  $M < 1.5 M_{\odot}$  increases very slowly with decreasing mass, there is an upper limit of magnitude extension of about 0.8 mag between main RC and SRC in our models. Moreover, with increasing age, the SRC becomes slightly bluer than FGB.

For the clusters with age  $< 1.2$  Gyr, the mass of all RC stars is almost larger than the critical mass. Therefore, the SRC caused by interactive binaries should not appear in these clusters. In addition, in old clusters, the initial mass of RC stars is low. If the mass is not enough to be increased to above the critical mass by accretion or merging, the SRC should not be produced by binary interactions in the old clusters. Moreover, if the fraction of binaries is too low, the SRC also could not be produced. Girardi et al. (2009) argued that the MS+red clump binaries cannot mimic the dual RC in NGC 419. In our models, the SRC stars are from the merged binaries and binary systems with mass transfer.

In this paper, we showed that binary interactions such as mass transfer and binary merging can produce an extended MSTO and dual RC in CMDs of intermediate-age clusters, whereas in actuality only a single population exists. Despite these, the rest of MS, subgiant branch and FGB are not clearly spread by the binary interactions. Interactive binaries can lead to an extension of MSTO rather than DMSTOs. For a cluster with  $Z = 0.008$  and age  $= 1.8$  Gyr, its isochrone can be spread down to  $\sim 1.5$  Gyr by interactive binaries. However, **only about 10% of binary stars lie between the 1.8 and 1.5 Gyr isochrones** in our models. Moreover, the SRC that is caused by interactive binaries should have an apparent age of about 1.1-1.2 Gyr. Although binary interactions cannot lead to the bimodal MSTO, the SRC in NGC 419 and extended MSTO of NGC 1846 may be partly from the mass-accreted or merged binary stars.

We thank the anonymous referee for his/her helpful comments and acknowledge support from the CPSF 20100480222, NSFC 11003003, 10773003, 10933002 and the Ministry of Science and Technology of the People’s republic of China through grant 2007CB815406.

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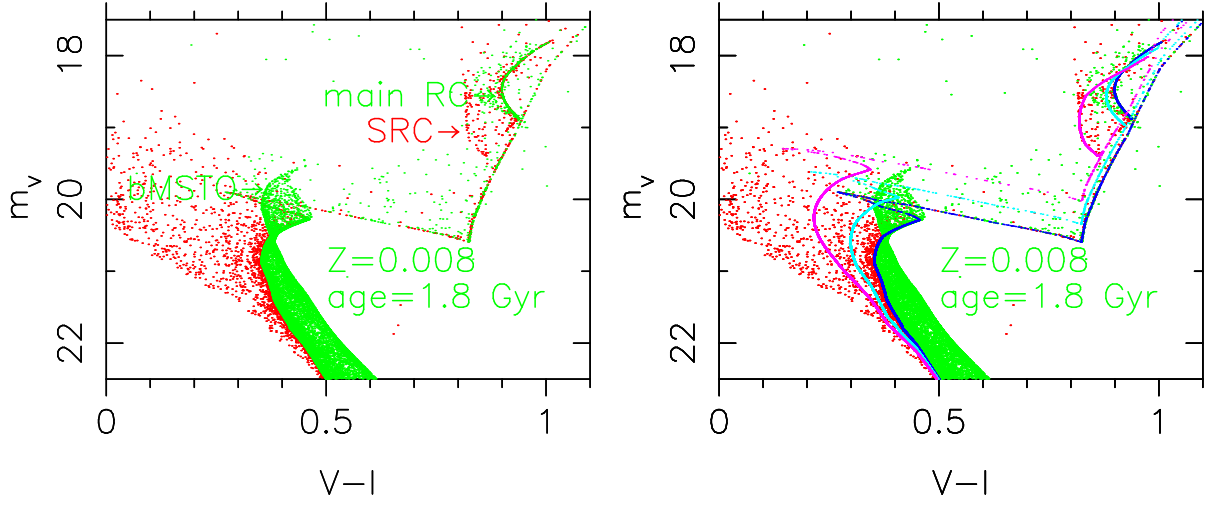


Fig. 1.— The CMDs of simulated BSP. Green shows the binaries almost without mass transfer, while red indicates interactive binaries. A distance modulus of 18.45 is adopted. The isochrones of SSP with the same  $Z$  but with different ages are overplotted on the CMD in the right panel (blue: 1.8, cyan: 1.5 and magenta: 1.2 Gyr).

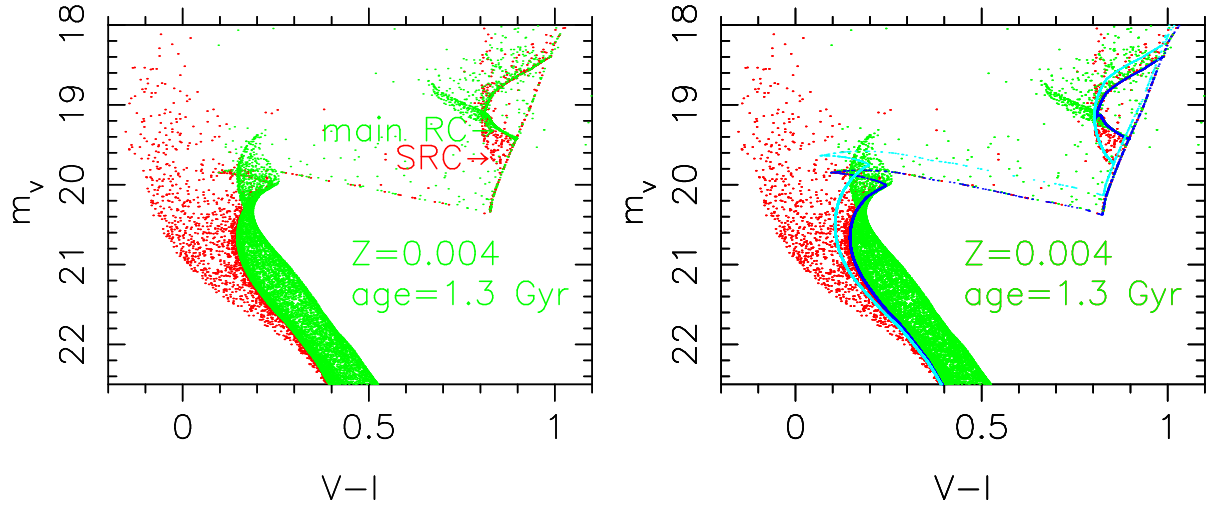


Fig. 2.— Same as Fig. 1. A distance modulus of 18.84 is adopted. The isochrones of SSP with the same  $Z$  but different ages are overplotted on the CMD in the right panel (blue: 1.3 and cyan: 1.1 Gyr).